No Slackers in Tourniquet Use to Stop Bleeding

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ABSTRACT

Background: Tourniquets on casualties in war have been loose in 4%–9% of uses, and such slack risks death from uncontrolled bleeding. A tourniquet evidence gap persists if there is a mechanical slack–performance association. **Objective**: The purpose of the present study was to determine the results of tourniquet use with slack in the strap versus no slack before windlass turning, in order to develop best practices. **Methods:** The authors used a tourniquet manikin 254 times to measure tourniquet effectiveness, windlass turns, time to stop bleeding, and blood volume lost at 5 degrees of strap slack (0mm, 25mm, 50mm, 100mm, and 200mm maximum). **Results:** When comparing no slack (0mm) to slack (any positive amount), there were increases with slack in windlass turns ($p < .0001$, 3-fold), time to stop bleeding ($p < .0001$, 2-fold), and blood volume lost ($p < .0001$, 2-fold). When comparing no slack to 200mm slack, the median results showed an increase in slack for windlass turns ($p < .0001$), time to stop bleeding ($p < .0001$), and blood volume lost ($p < .0001$). **Conclusions:** Any slack presence in the strap impaired tourniquet performance. More slack had worse results. Trainers can now instruct tourniquet users with concrete guidance.

Keywords: *hemorrhage, first aid, trauma, damage control, resuscitation*

Introduction

With a widespread reintroduction of emergency tourniquets to stop bleeding on the battlefield during current and recent contingency operations overseas, many users have gained recent experience.[1,2] Two tourniquet surveys of the experience of military users, in 1998 before the current war and in 2012 during the current war, show a 2000-fold increase in counts of devices used.[3,4] Along with much new experience gained, problems have been reported on occasion; loose tourniquets, which risk loss of hemorrhage control, have occurred in 4%–9% of casualties.[5,6] Investigators of tourniquet use have been unable to determine whether loose tourniquets were initially put on the limb loose or if the slack came later, possibly as the result of more bleeding from the limb or elsewhere.[5,7] Tourniquet slack has already been associated with increased risk of death by limb exsanguination.[5,8] One of the first steps in the application of a tourniquet of the windlass-and-strap design—the most common design used on the battlefield today—is to remove all slack before turning the windlass, which then completes the strap tightening.[9,10] However, experienced clinicians have reported anecdotally that if a casualty complains of pain, an inexperienced tourniquet user may not remove all slack so as to lessen jostling mangled limbs and thereby inadvertently prioritize comfort over hemorrhage control. Furthermore, adherence to the slack removal guidance may vary in part because of different training by the several military services, which each have multiple training programs and tourniquet instructions. Recently, King et al. reported in the *Journal of Special Operations Medicine* (JSOM) that tourniquet users, mostly Special Operations Forces (SOF) medics, routinely did not tighten emergency tourniquets sufficiently to stop bleeding and the distal pulse.[11] A recent analysis of recovered tourniquets used in war concluded that correct user actions (e.g., following the instructions to remove slack before twisting) led to effectiveness, but misuse did not.[12] A knowledge gap remains on the effect of slack on tourniquet performance. To fill this gap, the authors used a tourniquet trainer manikin that measures performance in order to provide users and trainers with evidence of the slack–performance association. The purpose of the present study was to determine differential results of tourniquet use with slack in the strap versus no slack before windlass turning, in order to inform development of best tourniquet practices.

Methods

The approved laboratory protocol (U.S. Army Institute of Surgical Research Regulatory Office, Practical Biomedical Engineering Research of Tourniquet Application and Use, L-12-009) was executed for the present study from May to August 2012. This study was conducted

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under a protocol reviewed and approved by the regulatory office and in accordance with good clinical practices. Investigators included a pair of cadets and a tourniquet researcher. All three users had been trained in tourniquet use prior to the study. All three were oriented to the manikin and its use.

The researchers used a HapMed™ Leg Tourniquet Trainer (CHI Systems, Fort Washington, PA); a simulated right-thigh body segment (leg number 000F) with an amputation injury just proximal to the knee was selected as the testing apparatus.[13] The medial hip–pelvic area had an embedded computer interface that included a smartphone-like touchpad. Software (version 1.9) internal to the manikin allowed the leg to stand alone and be operated by user input through finger touch on the pad. The manikin was laid on a desk in the laboratory and was operated in accordance with the manufacturer's instructions. The manikin had no fluid to simulate blood, but bleeding was represented by red lights that transilluminated the wound. The number of lights illuminated represented the intensity of bleeding—all lights on meant no control of bleeding; no lights on meant bleeding had stopped. Intermediate control was indicated by a few lights twinkling on and off. Arterial pulse was noted when palpable in the popliteal and femoral artery areas.

The system reported the blood loss volume as calculated using a linear equation from the arterial capacity and number of pulses before hemorrhage control. The touchpad readout for each iteration included the effectiveness of the bleeding control, the correctness of the placement of the tourniquet based on the scenario, the time to stop bleeding, the pressure exerted under the tourniquet, and the blood loss volume. The measurement of the time to stop bleeding started when the iteration began and stopped when the manikin sensed that the thigh was losing no more blood. Effectiveness was defined as the stoppage of blood loss and the termination of distal pulse. Iterations began with a tourniquet device laid out flat undone on the desktop and not yet applied to the thigh and ended when the user touched the touchpad button, believing that the hemorrhage was stopped. Scenario 1 of 7 preset scenarios was used; in it, the casualty had a small build and the setting was Tactical Field Care, a setting resembling civilian emergency care when not under gunfire or similar danger. The manikin settings also included a constant hemorrhage rate (635ml/min); the resulting bleed-out time in this scenario was 4 minutes, giving the user 240 seconds to successfully apply the tourniquet. Tourniquet devices, users, test iterations, and outcomes were uniquely identified. Users tightened the tourniquets to Combat Application Tourniquet Generation 6 (e.g., windlass turned) until simulated bleeding stopped. The manikin was designed to train users by providing differential performance feedback; we used the manikin in deconstructing the task of applying a tourniquet to study a specific step, slack removal.

The Combat Application Tourniquet (CAT, Composite Resources, Rock Hill, SC) is a strap-and-windlass design. One windlass turn is a 180° excursion arc, which is the limit of wrist supination in turning the windlass. The users by convention regrip the windlass after 180°; this arc is what they deem 1 turn.

The centerpiece of the present study was an experiment of slack in the strap (nonzero distances, a pool of 25mm, 50mm, 100mm, and 200mm samples) versus no slack on tourniquet performance. Performance criteria included hemorrhage control (yes–no), stopping the palpable pulse distal to the tourniquet (yes–no), time to stop bleeding (seconds), pressure applied to the skin by the tourniquet (mmHg), blood loss volume (ml), and the number of windlass turns executed (whole number). The user tightened the tourniquet using the windlass until simulated bleeding was believed to have stopped, based on visual inspection of the lights and palpitation for the distal pulse in the device.

Additionally, the slack–performance association was assessed at other degrees of slack in order to see whether the overall relationship was linear or otherwise. Besides 0mm, slack amounts were 25mm, 50mm, 100mm, and 200mm. These approximated 0, 1, 2, 4, and 8 in., which was a surrogate of a wide range of clinical use and could determine the shape of a scientific trend. Replicates at each slack distance were 120 at 0mm, 74 at 25mm, 20 at 50mm, 20 at 100mm, and 20 at 200mm.

Statistical analysis included use of descriptive statistics (means, medians, standard deviation, minimum, maximum, percentiles) and Wilcoxon's 2-sample test for comparison of means to the no slack data. Significance level was set at $p = .05$.

Results

In total, the researchers conducted 254 iterations of tourniquet use with different degrees of slack ranging from 0mm to 200mm (Table 1, Figure 1). Of the 4 outcomes (windlass turn number, time to stop bleeding, tourniquet pressure, and blood volume lost) for the 5 comparisons (no slack vs. slack, no slack vs. 25mm, no slack vs. 50mm, no slack vs. 100mm, and no slack vs. 200mm), all 20 results (4 outcomes × 5 comparisons) were statistically significant except 2; both were of pressures (Table 2).

When comparing no slack (0mm or 0in.) to slack (any positive amount), the results showed an increase with slack in windlass turns ($p < .0001$), time to stop bleeding ($p < .0001$), and blood volume lost ($p < .0001$; Table 1), and a decrease in pressure ($p = .0025$).

Table 1 *Tourniquet Outcome Data by No Slack Versus Slack*

Group	Variable	No.	Mean	SD	Minimum	Median	Maximum	p Value
No slack	Turns, No.	120	2	0.7	1	2	4	<.0001
	Time, sec	120	22	10.2	11	20	64	<.0001
	Pressure, mmHg	120	160	16.9	84	162	201	.0025
	Blood loss, ml	120	104	40.6	46	90	268	<.0001
Slack	Turns, No.	134	7	2.9	4	6.5	15	
	Time, sec	134	51	28.4	20	44	217	
	Pressure, mmHg	134	156	14.2	99	155	193	
	Blood loss, ml	134	218	106.6	84	184.5	532	

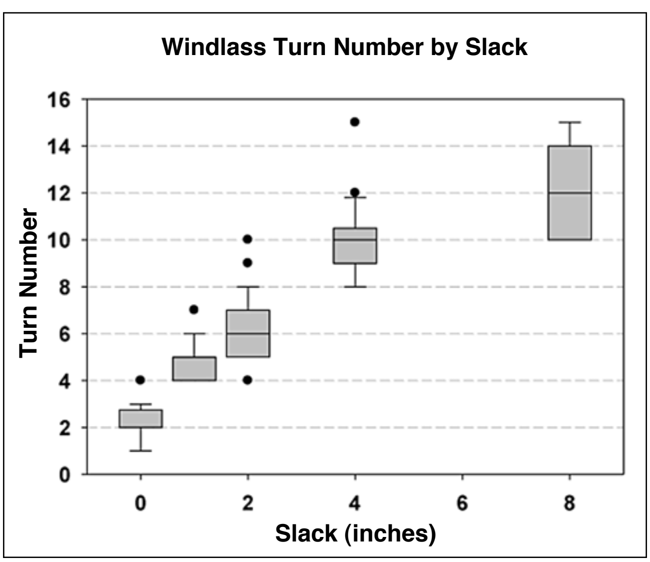
Note: Comparison is between no slack and slack (all nonzero slack samples were pooled into 1 sample).

When comparing no slack (0mm) to 25mm slack (1 in.), the results showed an increase with slack for windlass turns ($p < .0001$), time to stop bleeding ($p < .0001$), and blood volume lost ($p < .0001$), but there was no significant change in pressure ($p = .171$; Table 2, Figure 1). The turn numbers ranged from 1 to 15 and were low for 0 in. and rose stepwise at each slack increment. The turn number was associated positively and progressively with increasing degrees of slack. Increased turn numbers meant that it took more turns of the windlass in order to make the tourniquet effective.

When comparing no slack (0mm) to 50mm slack (2 in.), the results showed an increase with slack for windlass turns ($p < .0001$), time to stop bleeding ($p < .0001$), and blood volume lost ($p < .0001$), but there was no significant change in pressure ($p = .1075$).

When comparing no slack (0 mm) to 100mm slack (4 in.), the results showed an increase with slack for windlass turns ($p < .0001$), time to stop bleeding ($p < .0001$), and blood volume lost ($p < .0001$; Table 2), and a decrease in pressure ($p = .004$).

Figure 1 *Windlass turn number by strap slack. Windlass turn data are by slack degrees (0–8 in.). A turn number is a dot for iterations beyond the 5th and 95th percentiles. The gray box bottom and top represent the 25th and 75th percentiles, respectively. The median is a straight black line across a box.*



When comparing no slack (0mm) to 200mm slack (8 in.), the results showed an increase in with slack for windlass turns ($p < .0001$), time to stop bleeding ($p < .0001$), and blood volume lost ($p < .0001$), and a decrease in pressure ($p = .0084$). The differences in median performance results for all comparisons of no slack to 200mm slack for windlass turns (range, 2–13, 6.5-fold), for time to stop bleeding (range, 20–70 seconds, 3.5-fold), and for blood volume lost (range, 90–374ml, 4-fold) were all clinically significant, but the difference in pressure was not clinically significant (range, 162–151mmHg, Table 2).

We observed the expected positive relationship between time to stop bleeding and blood loss volume. As more time went by before control of hemorrhage, more blood was lost. The faster hemorrhage was controlled, the less the blood volume was lost.

When comparing slack length to outcome, we noticed an association. With increases in slack, outcomes (windlass turns, time and blood loss) were all worse performances.

Additionally, we noted that the users, the tourniquets used, and the manikin limb itself all experienced more difficulty with more slack. More slack led to more effort (supination torque) to control the simulated bleeding. Concurrently, there was more tourniquet wear and more manikin wear. At higher turn counts, users had more difficulty getting sufficient tourniquet pressure, had more device wear and tear, had more difficulty securing the windlass to its clip, and had more shallow tears of the manikin skin surface.

For effectiveness (yes–no), all three users had similarly high rates near 100%. The user learning curves in applying a tourniquet showed that the curve differed by variable, i.e., which outcome was chosen. For effectiveness (yes–no), the iteration where performance became satisfactory was near 1 for each of three users as there essentially was no learning, i.e., the behavior was successful

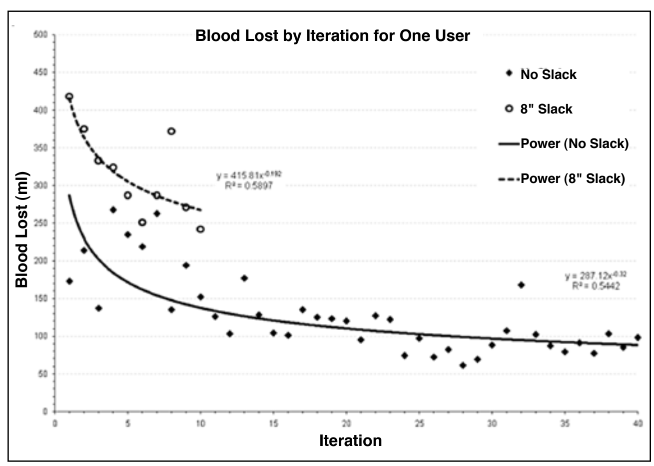
Table 2 *Tourniquet Outcome Data by No Slack Versus 25mm, 50mm, 100mm, and 200mm Slack*

Group	Variable	N	Mean	Std Dev	Minimum	Median	Maximum	*p* Value
No slack	Turns, No.	120	2	0.7	1	2	4	
	Time, sec	120	22	10.2	11	20	64	
	Pressure, mmHg	120	160	16.9	84	162	201	
	Blood loss, ml	120	104	40.6	46	90	268	
25mm	Turns, No.	20	5	0.9	4	5	7	<.0001
	Time, sec	20	35	8.1	26	32	50	<.0001
	Pressure, mmHg	20	157	10.6	140	156.5	181	.1710
	Blood loss, ml	20	151	35.0	86	144	214	<.0001
50mm	Turns, No.	74	6	1.2	4	6	10	<.0001
	Time, sec	74	42	25.0	20	37	217	<.0001
	Pressure, mmHg	74	159	14.6	131	158	193	.1075
	Blood loss, ml	74	168	58.8	84	156	317	<.0001
100mm	Turns, No.	20	10	1.1	8	10	12	<.0001
	Time, sec	20	74	31.5	39	64.5	167	<.0001
	Pressure, mmHg	20	152	11.5	139	151	179	.0040
	Blood loss, ml	20	305	88.6	177	290	477	<.0001
200mm	Turns, No.	20	13	2.0	10	13	15	<.0001
	Time, sec	20	75	21.8	44	70	123	<.0001
	Pressure, mmHg	20	150	16.6	99	151	177	.0084
	Blood loss, ml	20	379	87.2	242	374	532	<.0001

Note: All comparisons are pairs of no slack with an individual slack length.

from the beginning. There was therefore no change in behavior as the success rate was near perfect from the start. However, when time to stop bleeding was determined instead of effectiveness for 0mm slack, the learning curve for the three users was 33, 33, and 37 iterations (mean, 34; Figure 2). There was an offset (Figure 2), an increase in blood volume lost, with slack which included both setting and measuring the strap slack plus the time required to turn the windlass an extra number of turns in order to gain hemorrhage control. Setting and measuring the strap slack took about 4 seconds total; extra turns of the windlass took about 2 seconds per turn, which meant about 22 seconds (difference of medians, 8in. slack, 13, minus no slack, 2 = 11; 11 turns × 2 seconds/turn = 22 seconds). The majority of the blood loss [approximately 85% (22 seconds/26 seconds total)] was due to the increased time turning the extra turns and not from putting the slack into the strap. The manikin simulates blood loss linearly rather than being pressure driven in people; blood loss over time in human hemorrhage drops curvilinear with much early and little late.

Figure 2 *Learning curves for 1 tourniquet user by blood loss volume. This user had little change in performance at and after iteration number 33 indicating flattening of his learning curve. The slack [8 in. (200 mm)] sample showed a similar shaped curve for the beginning 10 iterations; however, there was an offset, an increase in blood volume lost.*



Learning curves differed by outcome varied more than 10-fold, an unexpected variance. Other slacks and learning curves produced similar results (Figures 3, 4, and 5). Note that 1 user (Figure 4, black box) performed better (faster) than the more experienced user (white circle), who showed no learning, a flat learning curve. Also note the occasional variability of the data as an outlier (Figure 4, top white circle, 217 seconds), which indicated an occassional snag in tourniquet application. In this iteration, 1 user had a difficulty with turning the 9th windlass turn and pinched and cut his thumb (Figure 4). Such an outlier, in our experience, represented well the vagaries of emergency tourniquet use in the real world where users may wrestle with tourniquets (Figure 4). The effectiveness-blood loss findings (Figure 5) indicated that effectiveness (yes–no) is a crude, fast, and binary assessment for trained users; whereas blood loss

Figure 3 *Learning curves for 1 tourniquet user by time to stop bleeding. This user had little change in performance at and after iteration number 37. This user is the same as that of Figure 2 which represents the same iteration data but for different outcomes (time in Figure 3 instead of blood loss in Figure 2).*

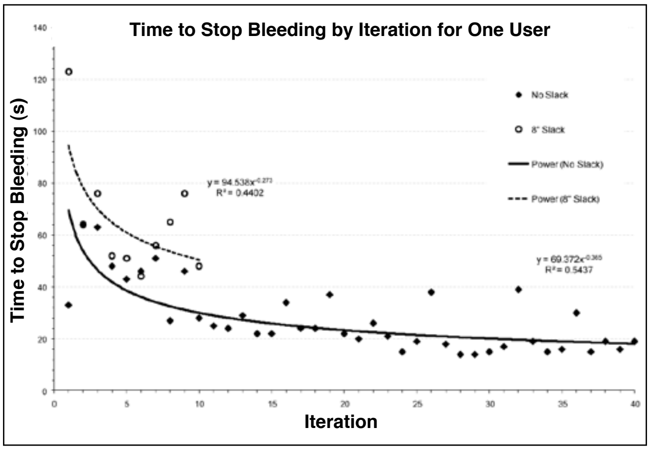
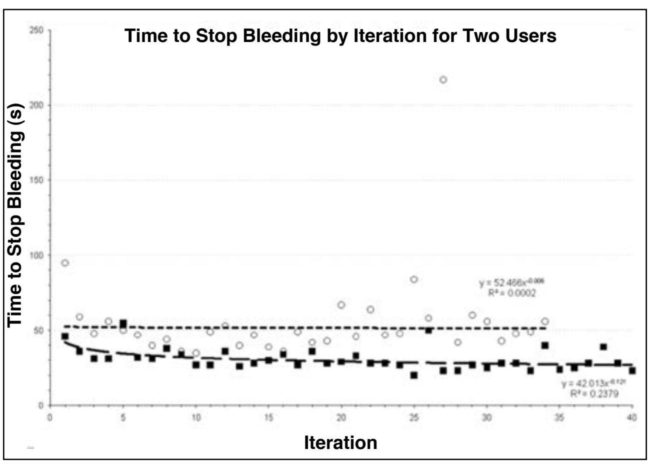


Figure 4 *Learning curves for 2 tourniquet users by time to stop bleeding with 2 in. of slack. Two users had little change in performance over the iterations for time to stop bleeding. The users had conducted many iterations before this pair of samples as this pair was later in the experimental order. Therefore, the 2 had learned a great deal before this pair, and the expectation of changes in performance were less.*

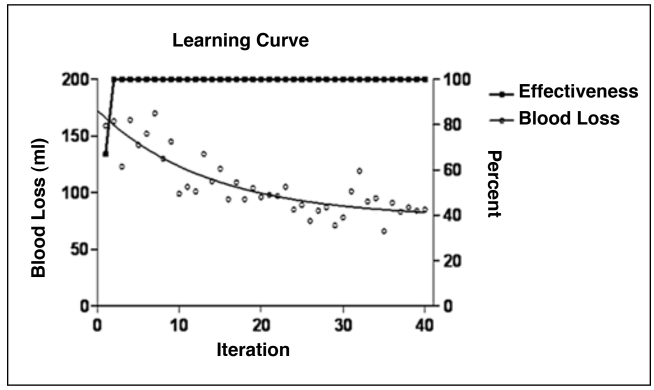


has gradations, takes longer to assess, and is more physiologically based. The results for time to stop bleeding were similar in these ways to blood loss.

Discussion

The main finding of the present study is that slack presence in the strap impairs tourniquet performance; the effect is plain, strong, and reliably reproduced. The amount of slack is associated positively with the windlass turn number, the time to stop bleeding, and the blood loss volume. In clinical care, slack risks death as loose tourniquets do not control bleeding. Slackers who

Figure 5 *Learning curves for tourniquet users by effectiveness and blood loss. Three users' data (no slack) averaged over 40 iterations had 2 learning curves, 1 for effectiveness (yes–no) and 1 for blood loss volume. One, effectiveness, was fast and steep; the other, blood loss, was slow and gradual. Effectiveness took 2 iterations before there was no further learning; whereas blood loss took 36, an 18-fold difference in the learning curves.*



shirk responsibilities in tourniquet use by not removing all slack before turning the windlass provide suboptimal performance. Instructors who do not emphasize slack removal are also slackers.

Tourniquet slack removal is an important step before windlass turning; and the evidence of the current study underscores, strengthens, and explains that importance. Tourniquet trainers may now reemphasize and better explain the importance of slack removal. The reason slack removal is critical is that effectiveness (control of hemorrhage) is attained with no slack faster, with fewer windlass turns, and with less blood lost. An additional benefit of no slack is to keep the tourniquet snugly in the desired place relative to the wound, but placement is less important than effectiveness. Effectiveness is about maximizing survival rates; placement is about minimizing morbidity rates. Both are important, but they are unequal in importance as life is more important than limb. It is easy to make a mistake regarding training priority, such as prioritizing nondisplacement of a tourniquet over its effectiveness. It is also easy to make a mistake regarding care priority, such as prioritizing comfort (pain avoidance) over survival (hemorrhage control). However, trainers can now make the main finding of the present study clear to users: no slackers!

The current experiment clearly indicates the mechanism of how users may place slack in tourniquets and the outcomes that result from both slack and no slack. The source of the slack in 1 clinical survey appeared to be prehospital users for the most part; 12 of the 13 loose tourniquets in that survey were prehospital tourniquets.[6] Although there have been educational warnings to trainers and tourniquet makers about slack, the rate of loose

tourniquets has actually increased.[14] The findings of the present study indicate that improvements in education and training are in order.

Minor findings of the present study dealt with ease of use. Slack made handling the tourniquet more difficult and more time consuming because it required more user skill and greater manual force to make the tourniquet effective. To make slackened tourniquets work, more force and finesse was required by users. The Combat Application Tourniquet, the most common battlefield tourniquet used in the U.S. military service today, had its Instructions for Use, the package insert, revised in 2009 in part because of the slack problem; the second step said to pull the strap *very tightly* (underlined in revised insert). It also provided a rule of thumb that when the strap is tightened satisfactorily, no more than three fingers will fit between the strap and the limb. However, that rule was recently removed in another revision because that amount of tightening was still inadequate.

The present study adds to a growing body of empiric knowledge that the best tourniquet practice is indeed to remove all slack to make the strap *very tight* before turning the windlass. A second ease-of-use phenomenon was stages of strap twisting. Initially during windlass turning, the inner strap wrapped flat on the windlass itself in primary twisting; the diameter of the twisting thus was that of the windlass, about 10mm. Later during windlass turning, secondary twisting occurred as the inner strap twisted over itself atop the windlass. Later during further windlass turning (and only in slack samples), tertiary twisting occurred as the inner strap twisted into pretzel-like loops while wrapping about itself over the windlass. Later during continued windlass turning (and only in 100mm and 200mm slack samples), quaternary twisting occurred as the inner strap twisted with its outer self-adhering strap, and both straps wound together into a ball around the windlass. The windlass–ball diameter was about the same as the strap width, 40 mm. Therefore, the amount of tightening with a single turn of the windlass ball was more than that of the windlass alone as their diameters differed roughly 4-fold; i.e., the strap excursion or tightening was roughly 4-fold different for each turn. If it were not for this quaternary twisting effect, in this case at 200mm, slack would have had an even larger effect on turn number at 200mm. For the first four samples (0mm, 25mm, 50mm, and 100mm), the relationship of the median turn number by sample appeared to be linear.

Another minor finding on ease of use came by happenstance. As part of another hypothesis test, we were using a particular CAT, that we designated CAT #1, for as many iterations as it could sustain before it became ineffective (e.g., broke), in order to evidence when wear and tear were too much. The CAT is described as a single-use medical device, but in the epidemic of casualties at the Baghdad emergency room, providers were pressed to reuse tourniquets.[5,6] CAT #1 survived 147 iterations with little wear; but when CAT #1 entered slack testing, it tore. The least slack caused the least wear and tear of CAT #1, and the most slack was associated with the most wear and tear. The greatest slack amount was tested last; and the force required quickly stripped the stitching, bent the buckle, pulled the plate, and warped the windlass. The last test iterations pulled the plate apart at its slot that passes the strap; this was a manageable problem that required sliding the plate close to the windlass before turning as the plate–windlass connection was separated at the slot break. The clip is attached at the far end of the plate from the windlass, so the break gap makes the windlass miss the clip so that it is not secured. Gap closure or taping can help secure such a displaced windlass. Although we could still make CAT #1 effective by using our skill and experience, CAT #1 was worn and torn too much for further testing. After 177 uses, CAT #1 was decommissioned. Progressive degrees of slack were associated positively with degrees of wear and tear. CAT #2 was used by a cadet, survived with little wear with all slack testing, and remains in service having succeeded in 269 iterations.

Study Limitations

Limitations of the present study are many. The experimental design did not include clinical care data, data from actual human thighs, or data from stressful situations such as emergency care on the streets or on the battlefield. The study did not address other interesting topics like the reasons that slack becomes present in tourniquets during emergency use because they were outside its scope. The amounts of slack, in hindsight, seemed clinically unreasonable at the high end, 200 mm, as the amount was so great as to fit another thigh in the strap loop; but such data gathered made the association clear—a scientific goal worth the laboratory time. Time to stop bleeding with slack in the tourniquet strap necessarily required a few seconds to place and measure the slack added. the extra time gave a small bias to the slack groups, albeit a small amount of blood loss. Learning curve explanations may be affected in part by such things as order of experiments since users that perform 1 experiment after another learn in that order, whereas those who perform in a different order may perform differently.

Conclusions and Future Directions

Future directions worthy of further study are numerous. These include consideration of user response to different programs of instruction regarding slack. Data gathering of training performance may include such things as

trainee performance metrics, instructor performance metrics, and programmatic performance metrics. Intratrainer performance tracking may show changes over time. User and trainer skill retention over time seems important as well, but data are lacking. User performance by various outcomes (effectiveness [yes–no], blood loss volumes, or time to stop bleeding) may indicate that learning curves differ by outcome in that effectiveness may require few training iterations, whereas minimizing time to stop bleeding may take many more. Associations among slack and performance (time to stop bleeding and blood loss volume) for other users may be needed to ascertain whether the relationships are linear or not. Besides the degree of slack, other user noncompliance with training may be associable with tourniquet wear and tear. As the variability of performance was introduced into the iterations by the users themselves and not the manikin, testing circumstances, or device models, so interuser and intrauser performance variation may be studied further. For testing tourniquet use techniques, the HapMed manikin system is useful not only for training users but also for generating knowledge; its use may address many of these issues.

In summary, the tourniquet experiment determined a negative slack–performance association for speed of use, windlass turn number, and blood loss. Any slack presence in the strap impaired tourniquet performance, and more slack had worse results. Learning curves for users varied more than 10-fold depending on whether, for example, effectiveness (yes–no) or time to stop bleeding was determined; the former was short, and the latter was long. With these results, trainers can now better instruct tourniquet users.

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